THERMAL EVOLUTION OF EUROPA'S ICY CRUST

C. Sotin[1], G. Choblet[1], J.W. Head[2], A. Mocquet[1] and G. Tobie[1], [1]Universite de Nantes, 2 rue de la Houssiniere, BP 92208, 44322 Nantes, France, sotin@chimie.univ-nantes.fr, [2]Department of geological sciences, Brown university, 02912 Providence, RI, USA.

Introduction: The Galileo mission revealed that Europa is a differentiated body with surface features including domes, faults and chaotic terrains suggesting the presence of an ocean in between the icy surface and the silicate core. The presence of domes suggests some forms of upwelling (thermal or/and chemical) linked to heat transfer by subsolidus convection in Europa's icy crust. This situation makes Europa a very appealing place for exobiology because life may develop at the interface between the deep water and the silicate core. For the last 5 years, we have developed models of Europa's internal structure and have obtained the following results :

- tidal forces produce very small amount of heat in the silicate layer and very large amount of heat in an ice shell close to its melting temperature [1].
- tidal heating varies in time, latitude and longitude resulting in strongly time dependent convection [2].
- tidal heating in the ice layer is large enough to prevent a complete freezing of the ocean without invoking the presence of ammonia [2].
- although tidal heating is an internal heating source, hot icy plumes can form at the interface with the ocean due to the strong temperature dependence of ice viscosity [3].
- For viscosities in agreement with those measured on terrestrial glaciers, tidal heating may heat up hot plumes leading to partial melting, which may explain the formation of chaotic terrains [4].
- Doppler shift measurements on a Europa orbiter should allow us to determine the presence of an ocean and to constrain the thickness of the ice crust [5]

Thermal convection models: The models use temperature-dependent viscosity for the ice and include viscosity dependent tidal heating. There has been some discussion about the viscous behavior of ice at stresses relevant to thermal convection models. One major issue is the stress exponent one must use. Figure 1 shows how viscosity varies as a function of differential stress : the lower the stress, the smaller the stress exponent. Thermal convection stresses are smaller than 10 kPa and deformation measurements of polar glaciers[6] suggest that below 10 kPa, ice behaves like a Newtonian material. The viscosity of ice at its melting point is on the order of 10^{14} Pa.s with upper and lower bounds equal to 10^{15} Pa.s and 10^{13} Pa.s, respectively.

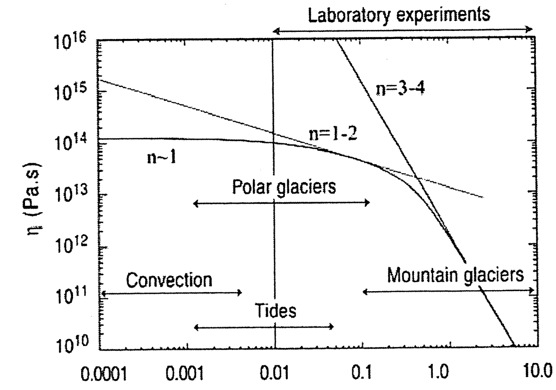


Figure 1 : viscosity versus differential stress at temperature close to melting temperature. The stress domain of different processes is indicated. The larger the stress, the larger the stress exponent.

The dynamics of convection is controlled by instabilities that form at the water-ice interface. These instabilities are time-dependent. The amount of heat, which can be removed from the base of the ice-crust, depends on the amount of internal (tidal) heating (Figure 2). An equilibrium is obtained for a thickness of 20 km for reasonable parameters of radiogenic heating in the silicate core and ice viscosity. One must note that the surface heat flux does not depend on the amount of tidal heating because it is controlled primarily by the viscous characteristics of the ice, which drive the instabilities in the conductive lid regime.

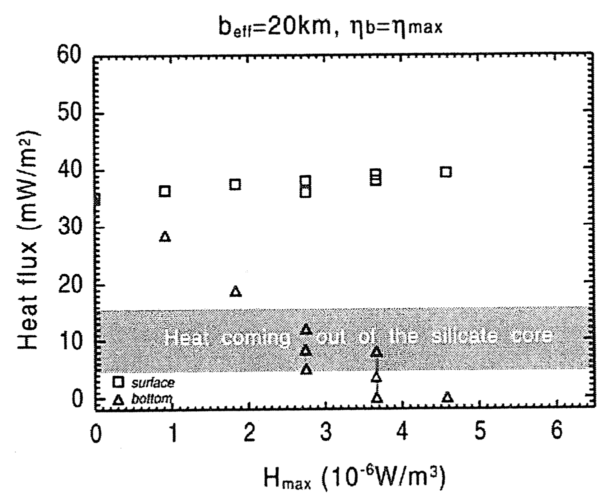
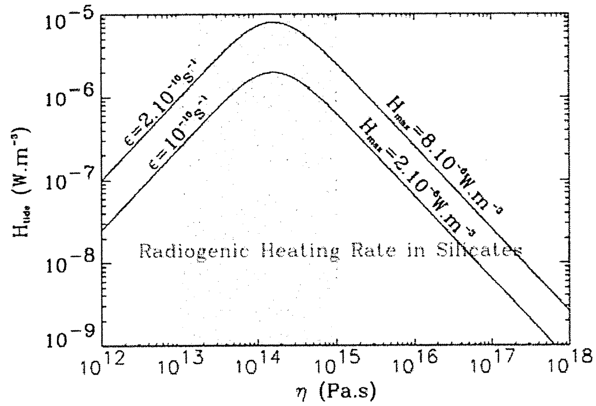


Figure 2 : Surface heat-flux versus tidal heating.

Tidal heating: Tidal heating is computed assuming that the material behaves like a Maxwell solid. If the viscosity of the material is larger than the Maxwell viscosity (ratio of shear modulus by orbital frequency), then tidal heating is negligible. Taking the present time values of the orbital parameters for Europa, the Maxwell viscosity is 3 10^{15} Pa.s and 1.5 10^{14} Pa.s for silicates and ice, respectively. Because the viscosity of partially molten silicates is at least 10^{18} Pa.s (value of mantle viscosity at mid-oceanic spreading centers), the amount of tidal heating deposited in the silicate core is likely to be negligible compare to radiogenic heating rate. On the other hand, the viscosity of ice close to its melting point is on the order of the Maxwell viscosity. Consequently, tidal heating is a major source of internal heating in the ice shell (Figure 3).



Expected value for ice viscosity near the melting point

Figure 3 : Tidal heating in the ice shell versus viscosity. The radiogenic heating rate per unit volume is represented for comparison.

For viscosities in between 10^{13} and 10^{15} Pa.s, the amount of tidal heating is 2 orders of magnitude larger than heating produced by the decay of long-lived radiogenic elements in the silicate core. As it can be seen on Figure 2, an equilibrium thickness of 20 km is obtained if a value of 3 10^{-6} W/m3 is used according to Figure 3. When the radiogenic heating rate was larger, the equilibrium thickness was smaller. A large range of parameters is investigated in Tobie et al., 2003 [2].

Because tidal heating depends on latitude and longitude, the equilibrium thickness may vary from place to place [7]. In the model described in Figure 4, it is found that the thickness varies between 17 km at the poles up to 29 km at the equator at the sub-jovian and anti-jovian points. The depth of any given isotherm varies also. For example, the 200 K isotherm, which is sometimes the one used for the definition of the lithosphere, varies from 13 km deep at the poles to 9 km deep at the equator. Variations of the lithosphere thickness may have implications on surface tectonics.

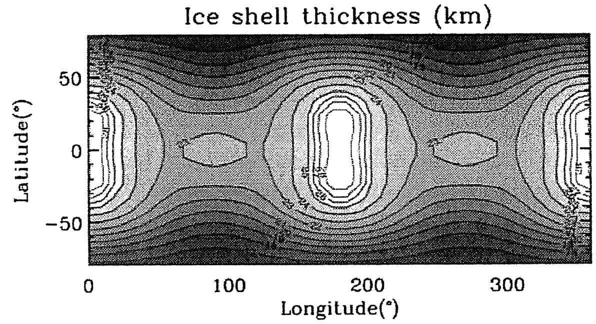


Figure 4 : Variations of the equilibrium thickness for a mean value of 22 km.

Another result of these models is that tidal heating may lead to melting in the upwelling plumes [4]. Because the density of water is larger than that of ice, subsidence may result in the formation of chaotic regions. The formation of partial melt is predicted if the ice viscosity at its melting point is equal to 10^{14} Pa.s, a value in agreement with available data (Fig. 1).

Conclusion and perspectives : The present study confirms that tidal heating plays a major role in the thermal history and dynamics of Europa. However, several problems remain. For example the topography of domes is difficult to explain due to the very thick conductive lid overlying the convective ice shell. In a companion paper (Tobie et al.), we investigate the interaction between the convective shell and the brittle elastic outer shell using damage rheology.

Although the results of Galileo and theoretical studies such as this one strongly suggest the presence of an ocean, one must admit that there is no direct measurement that such an ocean exists. An orbiter around Europa could achieve this goal and put constraints on the thickness of the ice crust.

References:

[1] Tobie et al. (submitted), *Icarus* [2] Tobie et al. (in press), *JGR*. [3] Deschamps F. and Sotin C. (2000) *JGR, 90,* 1151–1154. [4] Sotin C. et al. (2002) *GRL., 32,* A74. [5] Castillo et al. (2000) *C.R.A.S., 90,* 1151–1154. [6] Montagnat and Duval (2000) *EPSL*, 183, 179-186 [7] Ojakangas G.W. and D.J. Stevenson (1989), *Icarus*, 81, 220-241.